An Optimized Shipboard HF Loop Antenna for NVIS Link

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Abstract – *Ship's HF loop antenna with capacitive load is optimized for NVIS link with application of Method of Moments. Optimizing criteria for electric current distribution on antenna structure is set by means of greater power radiation of linear horizontal polarization wave in zenith direction. Starting values for capacity load of loop antenna is given by equivalent two-wire transmission line analysis. Optimized ship's loop antenna has appropriate properties for NVIS radio communication.*

Keywords - *Method of Moments, NVIS Loop Antennas, Shipboard HF Antennas*

1. INTRODUCTION

Near Vertical Incident Skywave technique (NVIS) provides radio communication beyond line of sight without any type of repeater system. Power emission of electromagnetic wave in approximate zenith direction and wave reflection results in specified ionosphere layer produces circle area coverage with point of radiation in the centre. NVIS radio link range is from few tens to few hundreds of kilometers. Due to near vertical path NVIS radio link depends only on ionosphere properties in examinated location in specified time. Properties are listed in [1] and [2]. Highest useful frequency of vertical ionosphere wave for mid-latitude is mostly in 2 MHz to 10 MHz range. Use of horizontal polarization of vertical Skywave successfully suppresses interference of Skywave and ground wave.

Specified features indicate that establishing of NVIS radio link depends crucially of working frequency chosen and antenna properties. Main goal of this paper is optimization of antenna mounted on small metal ship for NVIS link by use of numerical procedure. In [3] results are published for optimized antenna mounted on vehicle. The significant differences in results were found due to antenna platform dimension and electromagnetic properties of sea surface compared to land.

2. SHIPBOARD HF ANTENNA SYSTEM MODELING

Integral component of antenna system, apart from antenna itself, is its environment spreading to distance of few wavelengths. In considered frequency band wavelength is 150 to 30 m, therefore antenna system consists of antenna, ship's structure and involved part of sea surface. In [4] is shown that Method of Moments is efficient numerical procedure for analysis of radiation structures with dimensions in the wavelength order of value. In this paper commercial version of NEC-2 software is used and software limits are given in [5]. Wire model of metal ship, 31 m length and 6 m wide on water level and maximum 8.15 m height from sea surface, is shown in Fig. 1. This thin wire model contains 962 straight ideal conductivity thin wires. For considered frequency band approx. 1 m length for thin wires or segment is selected. Radius a of thin wire related to segment length Δl and wavelength λ should be $a < 0.5\Delta l$ and $2a\pi << \lambda$, respectively. When modeling conducting surfaces with wire grid, distance of axes and radius of straight wires approximately equal to area of modeled surface is desired. In accordance to all criteria, radius of 50 mm is chosen for all ship's model wires.

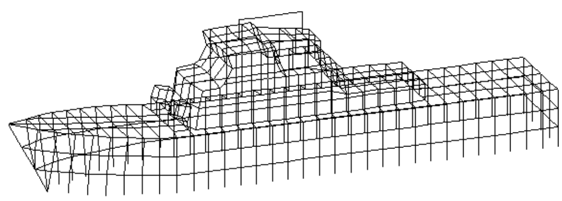

Fig. 1. Antenna system modeled with metal wire

In accordance to [5] sea surface is possible to model on few various ways. If it is equivalent to ideal conducting grounded plane standard mirroring of radiated structure in application of Methods of Moments is used. Good conductors are materials for which the density of conducted current is much greater than density of displacement current, therefore $\sigma >> \omega\varepsilon_0\varepsilon_r$. Average electrical conductivity of sea water is $\sigma \approx 5$ S/m and relative dielectricity is $\varepsilon_r \approx 81$, so stated claim to frequency of near 10 MHz is fulfilled. Therefore sea surface is modeled with ideal conducted grounded plain. Free ends of ship's model thin wires on Fig. 1 lay in this plain.

HF NVIS antenna is vertical loop square antenna mounted along centerline on highest part of ship. Antenna dimension is given on Fig. 2. Examinated antenna with three straight ideal conductivity thin wires with 25 mm radius is modeled. Horizontal wire 4 m long is divided on six segments in application of Methods of Moments. Vertical wire in antenna front-end, 1.18 m long, contains two segments and voltage source 1V/0° in point of wire connection with ship's structure. Vertical wire in antenna back-end, 1.38 m long, in two segments is divided.

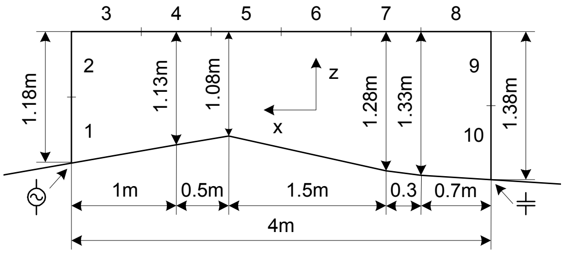

Fig. 2. Loop antenna dimensions with 1-10 specified segments

Simulating antenna structure model it is shown that the first resonance frequency appears at 12.23 MHz. Related to NVIS frequency range it belongs to electrically small antennas for which radiation efficiency are examinated in [6] and [7]. The part of energy which antenna exchanges with near field is increased with decreasing of dimensions. In the consequence antenna radiation resistance against to loss resistance is decreased and imaginary part of antenna input impedance is increased. Therefore electrically small antenna regularly has very small radiation efficiency and very large Q factor. In that case the efficiency of antenna input impedance matching network is low due to large losses in circuit elements caused by large currents and voltages. Losses are minimal, therefore efficiency of antenna matching network is maximal if circuit consists only of capacitors and imaginary part of antenna input impedance is inductive as it is case for small loop antenna.

3. VERTICAL LOOP ANTENNA FOR NVIS LINK

Radiation in vertical direction (in direction of +z-axe shown in Fig. 2) is defined by distribution of electrical current on loop antenna's horizontal conductor and distribution of current on the part of conducting ship's structure below that antenna's conductor. This distribution can be changed with loop antenna capacity loading connected in the point of antenna back-end wire connection with ship's structure. Loop antenna's horizontal conductor and involved part of ship's structure can be substituted as in Fig. 3, with equivalent lossless two-wire transmission line $l = 4$ m long with $2a = 50$ mm radius conductors distanced $2h = 2.40$ m in free space. Average height h is derived from area of actual loop antenna.

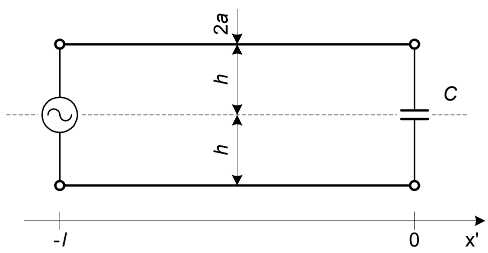

Fig. 3. Loop antenna's horizontal conductor equivalent transmission line

Two-wire transmission line characteristic impedance is:

$$Z_0 = \frac{120}{\sqrt{\varepsilon_r}} \ln\left[2\left(\frac{2h}{2a}\right)\right] = 547.7\Omega \tag{1}$$

Total electric current on equivalent transmission line is:

$$I(x') = I_0^+ \left[e^{-j\beta x'} - \Gamma e^{j\beta x'}\right] \tag{2}$$

where I_0^+ is magnitude of +x' direction propagated current wave, β represents phase constant and Γ is reflection coefficient on capacitive load. Total electric current, with $\beta l/2 << 1$, has its maximum in the middle of transmission line, $x' = -l/2$, if capacitance of load is:

$$C \approx \frac{2c}{(2\pi f)^2 Z_0 l} = 6.94 \cdot 10^3 \frac{1}{f^2} \tag{3}$$

Fig. 4 represents frequency dependence on loop antenna capacity load value, for which the current in the middle of horizontal part of antenna has its maximum, is determined according to relation (3) and by means of simulation on antenna structure model. Deviation among those determined capacity values is in range from −11.4% to +1.4%, in frequency band from 2 to 10 MHz, respectively.

Normalized absolute values of electric current distribution on segments (no. of segments is given on Fig. 2) of shipboard vertical loop antenna optimized for NVIS application are shown on Fig. 5. Values are determined by means of simulation on antenna structure model for previous calculated capacity load values. Obviously, in the middle of horizontal loop antenna's conductor always is maximal current value. It provides maximum radiation of linear horizontal polarized electromagnetic wave in zenith direction.

Antenna's input impedance varies from $(0.010 + j36.7)\,\Omega$ to $(4.5 + j212.3)\,\Omega$ in frequency range from 2 to 10 MHz, respectively. That range is significantly decreased related to appropriate change of loop antenna input impedance without capacity loading. In so doing, did not consider losses due to antenna structure finite electrical conductivity.

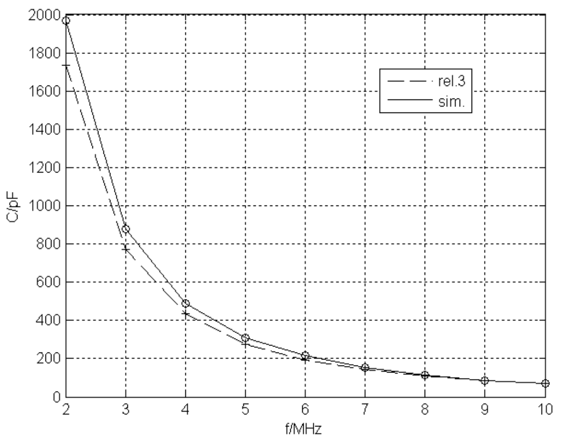

Fig. 4. Capacity load value frequency dependence

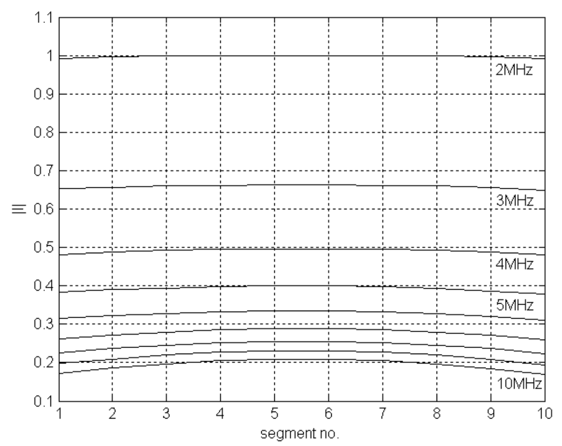

Fig. 5. Electric current normalized absolute values on optimized antenna's segments

4. NVIS LOOP ANTENNA RADIATION PATTERN

Shipboard loop antenna optimized for NVIS link radiation pattern is determined by means of simulation on antenna structure model. Antenna's radiation pattern cut in horizontal (for $\theta = 45°$) and vertical (for $\Phi = 90°$) plane on 5 MHz is shown in Fig. 6 with solid line for linear horizontal polarization and with dashed line for linear vertical polarization of radiated wave. Radiation pattern shape is nearby equal in frequency range from 2 to 10 MHz. It is shown that required performance of antenna for NVIS link is realized: radiation of linear horizontal polarization wave mostly in vertical direction and radiation of linear vertical polarization wave mostly in horizontal direction. Frequency dependence of examined antenna gain for radiation of linear horizontal polarization wave in vertical direction, $\theta = 0°$ is shown on Fig. 7. In considered frequency range maximum value of gain is 4.29 dB_i on 2 MHz and minimum value of gain is -0.73 dB_i on 7 MHz.

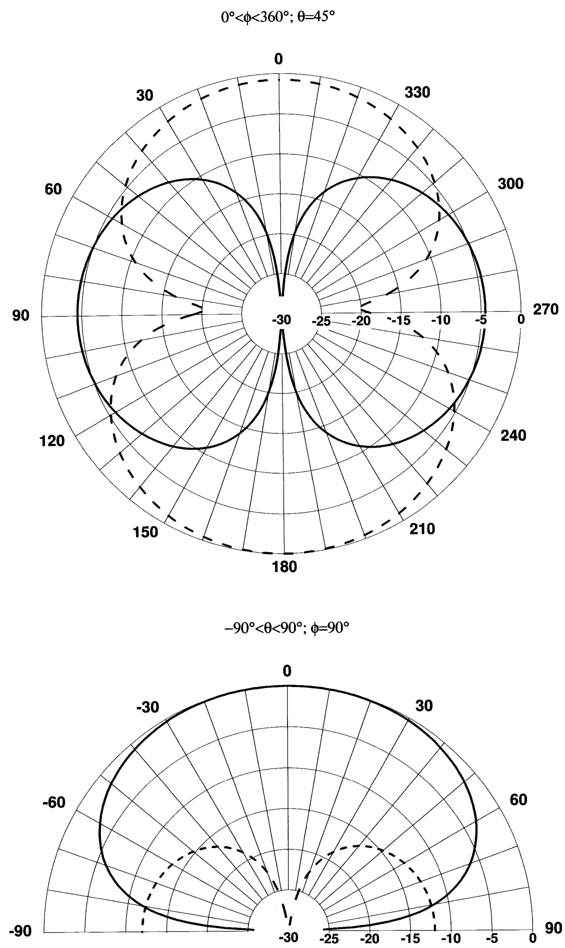

Fig. 6. Vertical loop antenna radiation pattern

More useful parameter of HF NVIS antenna is beam efficiency. According to [8] beam efficiency for antenna with main lobe in z-axes ($\theta = 0°$) direction is equivalent to ratio of radiated power in solid angle of $2\theta_1$ and by antenna total radiated power:

$$BE(\theta \le \theta_1) = \\ = \frac{1}{2\eta_0 P_{rad}} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\theta 1} \left(|F_\theta|^2 + |F_\phi|^2 \right) \sin\theta \, d\theta \, d\phi \tag{4}$$

where η_0 represents free space wave impedance, $|F_\theta|$ and $|F_\Phi|$ represents absolute value pattern function, respectively. If θ integration range is divided into N parts and Φ integration range divides into M parts, then integral in (4) can be approximated by order:

$$BE\left(\theta \le \theta_1\right) = \frac{1}{2\eta_0 P_{rad}}\left(\frac{\theta_1}{N}\right)\left(\frac{2\pi}{M}\right)\sum_{j=1}^{M}\left[\sum_{i=1}^{N}\left(\left|F_{\theta_i}\right|^2+\left|F_{\phi_j}\right|^2\right)\sin\theta_i\right] \quad (5)$$

where value in the middle of any angle increment is:

$$\theta_i = \frac{\theta_1}{2N} + (i-1)\frac{\theta_1}{N} \qquad \phi_j = \frac{2\pi}{2M} + (j-1)\frac{2\pi}{M}$$

Frequency dependence of examinated antenna beam efficiency for $\theta_1 = 45°$, M = 3 and N = 24 is shown on Fig. 7. In considered frequency range maximum value of beam efficiency is 35.6% on 2 MHz and minimum value of beam efficiency is 16.4% on 7 and 8 MHz.

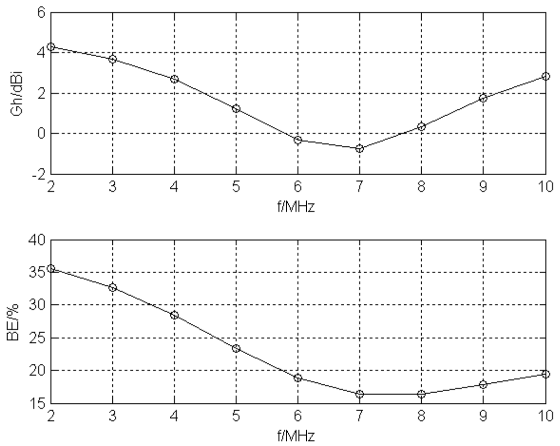

Fig. 7. Optimized antenna gain and beam efficiency frequency dependence

5. CONCLUSION

Shipboard HF NVIS antenna should radiate as possible greater power of linear horizontal polarization wave approximate in zenith direction in frequency range from 2 to 10 MHz. Radiation power of linear vertical polarization wave and input impedance varies should be small as possible. Specified demands can be achieved by vertical rectangle loop antenna with capacity load.

Antenna's structure electric current distribution is optimized by application of Method of Moments in accordance with specified criteria. In so doing, loop antenna and ship's structure are modeled with ideal conducting thin wire grid, and sea surface is replaced by ideal conducting grounded plane. Starting values of loop antenna load capacity in the process of current distribution optimization for NVIS link, are derived by analyses of equivalent electric circuit with two-wire transmission line. Optimized antenna in specified frequency range has beam efficiency from 16.4% to 35.6% for desired angle $\theta \le 45°$.

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